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Charles V. Schwab

Iowa State University, cvschwab@iastate.edu

I. Joe Ross

University of Kentucky

Gerald M. White

University of Kentucky

Donald G. Colliver

University of Kentucky

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WHEAT LOADS AND VERTICAL PRESSURE DISTRIBUTION IN A FULL-SCALE BIN PART I — FILLING

C. V. Schwab, I. J. Ross, G. M. White, D. G. Colliver

ABSTRACT. *Flat-bottom cylindrical grain bins are subjected to unique loads and pressures during the filling process. The vertical and lateral loads imposed on a bin wall and the vertical load on a bin floor by wheat during filling were measured. The radial distribution of vertical pressure during filling was also measured. The vertical pressure was determined to be dependent on the radial location and was not uniformly distributed. The load distribution in a bin with an H/D ratio of 3 was 83% on the floor and 17% on the walls. Three widely used prediction equations of Janssen, Reimbert, and Walker were compared to the measured loads and pressures and were determined to have similar shapes but different parameters for a best fit to observed data. Keywords. Wheat pressures, Bins loads, Full-scale measurements, Radial variation.*

This study investigated the influence of geometric, operational, and physical factors on wheat loads and vertical pressure distribution in a full-scale grain bin. Others have investigated pressures in model bins using different types of granular substances and nontraditional bin wall materials. Mason (1983) and Deutsch and Schmidt (1969) used model bins made with Plexiglas. Different surface characteristics such as the coefficient of friction between the bin wall and grain influenced the results. Pieper (1969), Smid (1972), and Mason (1983) used sand as the granular substances in their model studies. No modeling factors were developed in these studies to extrapolate the findings of nontraditional materials and granular substances to galvanized steel bin walls and cereal grains.

Experimental results obtained from previous studies exhibited large amounts of variation between studies. Different testing procedures caused by physical restrictions influenced the measured granular loads and pressures. Horabik et al. (1988) concluded that the orientation of the grain had a significant influence on the measured load distribution. The load and pressure measuring devices contributed significantly to the variation between studies.

An important assumption used in the theoretical development of several equations for predicting pressures in a grain bin has been that the vertical pressure across the radius of the bin is uniform. Bovey (1904), Saul (1953), and Dale and Robinson (1954) reported that the distribution of the vertical pressure is not uniform as assumed by Janssen (1896). Lenczner (1963) found a uniform distribution of vertical pressure for the static grain condition and an uneven distribution during discharge. The information of radial variation of vertical pressures in these experiments was obtained by pressure diaphragms. Pressure diaphragms introduced measurement errors because of interaction of granular substances with the measuring surface. Thompson and Williams (1994) reported that the vertical floor pressure was influenced by the flexibility of the bin floor. The vertical floor pressures in a model bin with a center supported floor were different from the bin with peripheral supported floor.

The influence of radial locations on grain pressure was examined in this study using a full-scale storage bin and wheat. The overall objective of this research was to increase the understanding of wheat loads and vertical pressure distribution during filling, enabling the development of an accurate method for wheat load and pressure prediction.

Article was submitted for publication in April 1994; reviewed and approved for publication by the Structures and Environment Div. of ASAE in August 1994. Presented as ASAE Paper No. 89-4007.

This article is published with the approval of the Director of the Kentucky Agricultural Experiment Station and designated Paper No. 89-2-122.

Major funding for the research reported in this article was provided by the Equipment Manufacturing Institute, Chicago, Illinois, and the University of Kentucky Agricultural Experiment Station. Part of the equipment used in this research was donated by Brock Mfg. Co. Inc. of Milford, Indiana; Butler Mfg. Co. of Kansas City, Missouri; Chief Industries Inc. of Grand Island, Nebraska; Clayton & Lambert Mfg. Co. of Buckner, Kentucky; and Mix-Mill Mfg. Co. Inc. of Bluffton Indiana.

The authors are Charles V. Schwab, ASAE Member Engineer, Assistant Professor Agricultural and Biosystems Engineering Dept., Iowa State University, Ames; I. Joe Ross, ASAE Fellow Engineer, Professor and Chairman, Gerald M. White, Professor Emeritus, and Donald G. Colliver, ASAE Member Engineer, Associate Professor, Agricultural Engineering Dept., University of Kentucky, Lexington.

EXPERIMENTAL METHODS

The experiments were conducted in a 4.1-m-diameter, smooth galvanized steel bin that was located outside. A schematic diagram of the grain bin research facility is shown in figure 1. The test bin was filled from a centrally located spout at the top. The filling spout extended down into the test bin a distance of 6.1 m to simulate the vertical fall height typical of spout-filled bins with an H/D ratio of 3.0. The cylindrical test bin wall was independently suspended by a rigid support frame as illustrated in figure 2. The isolation permitted the measurement of the floor loads independent of the wall loads.

The flat test floor was composed of five concentric rings and the center orifice slide gate ring. Each concentric ring

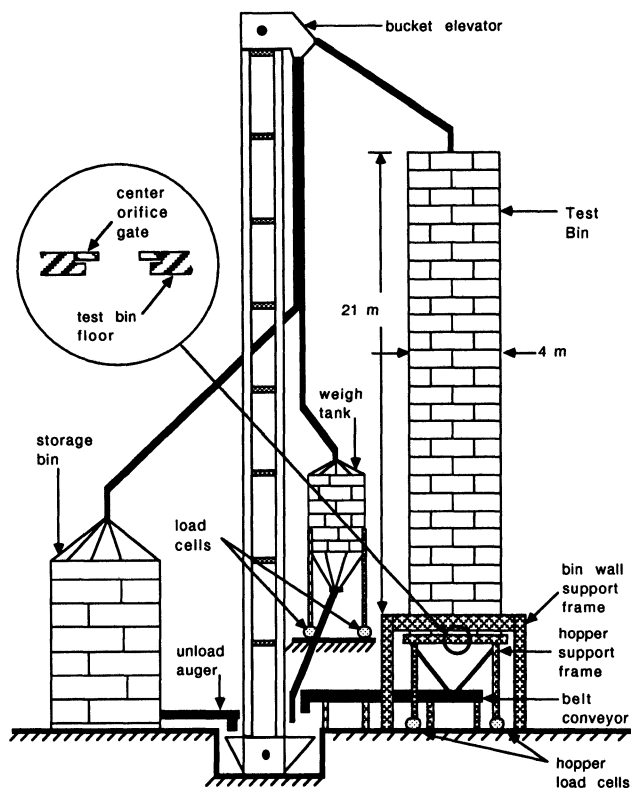


Figure 1—A schematic diagram of the University of Kentucky grain bin research facility.

had an area of 2.6 m² which was approximately 20% of the total floor area. The area of the nonload sensing slide gate ring was approximately 1.9% of the total floor area and was not considered in vertical pressure distribution calculations. Variation of elevation across the floor was less than 20 mm. A clearance of approximately 3 mm existed between the edges of any two rings. The rings were connected to a support frame by a set of hinges and compression load cells. Each load cell had an accuracy of 0.05% of 44 kN full-scale load. A schematic diagram of the junction between the concentric ring floor and the support frame is shown in figure 2. Radial location of a ring was determined by the ratio of the average ring radius divided by the radius of the test bin. The five rings are labeled by the percent of radius which are 32, 56, 72, 84, and 95%.

The hopper frame, the I-beam support frame, and the concentric ring floor were supported by four compression cells under each leg of the hopper frame. Each cell had an accuracy of 0.09% of the 889 kN full-scale load capacity. The combined measurements of the four cells gave the total floor load exerted by the wheat in the test bin.

Each component of the floor measurement system was structurally rigid to prevent deflection influences on measured results.

The physical properties of the wheat were determined periodically and remained constant throughout the experiment. The moisture content of the wheat was measured by the oven method, ASAE Standard S352.2 (1993). Bulk density was determined by a Winchester weight per unit bushel tester. The angle of repose was measured during the bulk density test. The content of the tester loading funnel was emptied onto a level surface and

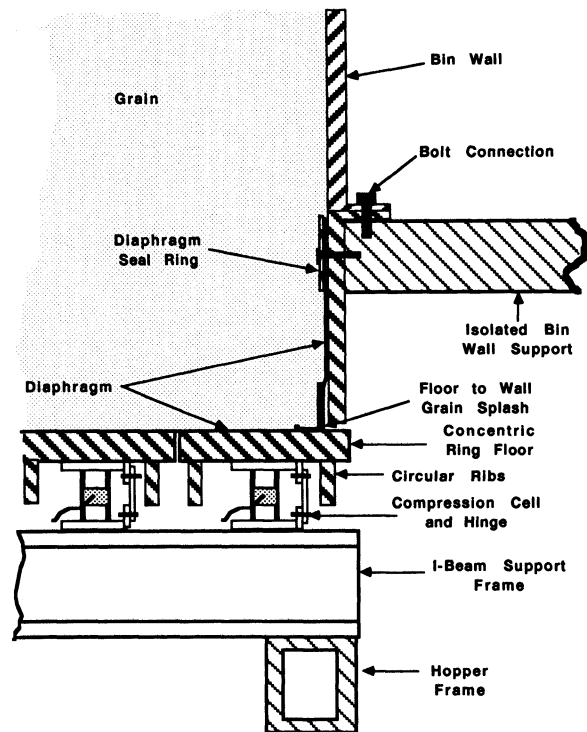


Figure 2—Cross-sectional view of the test bin wall and floor interface load cells.

the angle was measured by a protractor. A summary of the physical properties of the soft red winter wheat is in table 1. The physical properties of specific gravity, fineness modulus, bulk modulus, and physical dimensions of the wheat are available in Schwab (1989).

The vertical and horizontal bin wall strains were measured by metallic resistance strain bridges attached to the test bin wall. A strain bridge was comprised of two active and two temperature compensating strain gages forming a full-bridge configuration. The two temperature compensating gages were isolated from bin wall strain. A detailed description of strain measurements is given in Schwab (1989). The lateral pressure measurements had a full-scale range of 40 kPa with a resolution of 0.4 to 1.6 kPa for bin wall thickness from 1.5 to 2.7 mm, respectively. The vertical wall load measurements had a full-scale range of 300 kN with a resolution of 14 to 6 kN for the bin wall thickness of 1.5 to 2.7 mm, respectively. The test bin was divided into seven levels of strain measurement, as depicted in figure 3. At each level of measurement, there were two vertical and two horizontal strain bridges 154° apart. The test bin construction interfered with strain gage placement at 180° apart because of the uneven number of bin panels with flanges that comprised the circumference. Each pair (vertical and horizontal) was located near the center of a bin wall section.

Table 1. Summary of physical properties of soft red winter wheat

Moisture content (w.b.)	13.2%
Bulk density	721 kg/m ³
Angle of repose	27°

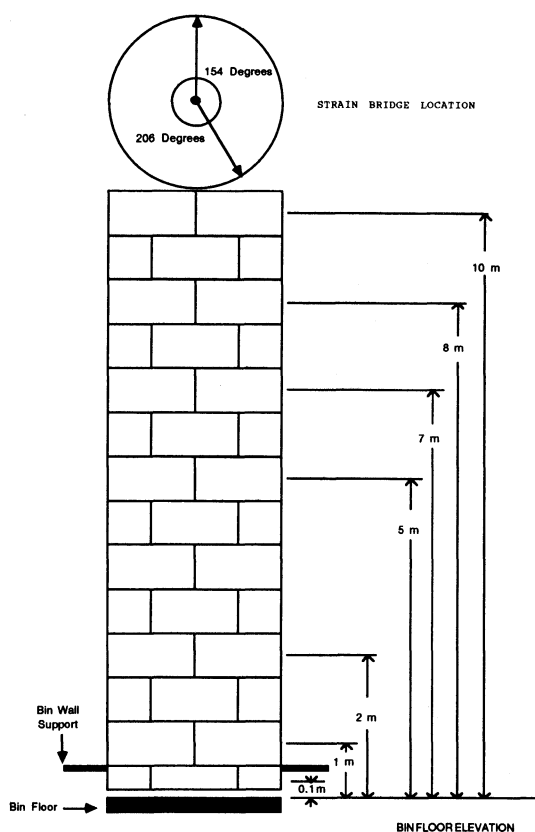


Figure 3—Strain gage bridge elevations on the test bin wall.

Thirty-nine channels of load transducers and 28 channels of strain bridges were connected to switching and balancing units. Each channel had the output independently zeroed and continuously excited. The outputs of the channels were manually scanned and then recorded with a computer program. The calculated sampling rate of the system was 0.4 Hz based on the average time for reading and recording channels of information.

Calibration of the load transducers on the test bin was accomplished by placing water in the bin to a maximum depth of 3.1 m. The loads from the water pressure were measured and recorded at 30.5 ± 0.03 cm increments while filling and draining. This procedure was replicated three times.

The grain loads and pressures in the test bin were examined for eight nominal filling depths. Nine replications were completed for each height of grain to diameter of bin ratio (H/D) of 1.8 and 3.0. Loads at all radial positions defined by the concentric ring floor were measured during the tests as were the strains at all seven levels of instrumentation on the bin wall. During filling, increments of grain were loaded into the weigh tank and the weight was recorded. The weigh tank had an accuracy of 0.5% of the full-scale load of 178 kN. The grain was then placed in the test bin. The time required to fill the test bin was 2.1 and 3.3 h for tests with an H/D ratio of 1.8 and 3.0, respectively. After each weigh tank load had been transferred, the load and strain measurements were recorded and the actual grain depth was measured at two locations along the diameter of the bin by a weighted tape measure. An equivalent depth was calculated from a linear

approximation of the cone-shaped surface to a level surface.

RESULTS

MODEL COMPARISONS

The observed filling loads and pressures were compared to three existing models that are used in design codes. The model predictions of Janssen (1896), Reimbert and Reimbert (1976), and Walker (1966) were fitted to the experimental data for the filling loads and pressures. The parameters for each prediction model were estimated by the nonlinear regression technique in SAS (1982). The coefficient of friction and the ratio of lateral to vertical pressures (μ' and k) for Janssen's and Reimbert's equations were bounded by preset limits. The coefficient of friction ranged from 0.01 to 0.90 and the ratio of lateral to vertical pressure ranged from 0.4 to 0.6. The nonlinear regression technique used a least squares grid search for different combinations of the parameters within the selected range. The optimal ratio of lateral to vertical pressures was determined by the nonlinear regression technique. The distribution factor (D') for Walker's model was fixed at unity and the grain parameter B was fitted. The depth measurements of the grain were changed to an equivalent depth to account for the cone-shaped surcharge which resulted from the filling method.

The parameters for the prediction models that were estimated from the nonlinear regression of the total floor loads are given in table 2. The degree of fit for the prediction models was estimated by the calculated coefficient of determination value. All models were equally effective in prediction of the total floor load. The differences between the predictions of the three models using the fitted parameters are not distinguishable from each other as illustrated in figure 4. The variation between measured loads at similar depths for different replications was less than 13% of the maximum load for each depth. The replications were conducted over a period of four

Table 2. Parameters of the three prediction models estimated by nonlinear regression of the total floor load during filling

Models	Parameters	r^2 Values	Error of Estimate (%)
Janssen*	$\mu' = 0.088^\dagger$ $k = 0.40^\ddagger$	0.998	1.96
Reimbert §	$\mu' = 0.03$ $k = 0.60^\ddagger$	0.998	2.08
Walker	$B = 0.0352^\#$ $D' = 1.00^{**}$	0.988	1.95

* Janssen's equation; $p_v = \frac{\gamma g R h}{k \mu'} \left[1 - \exp \left(\frac{-k \mu' y}{R h} \right) \right]$

† Coefficient of friction of grain on galvanized steel.

‡ The ratio of lateral to vertical pressures.

§ Reimbert's equation; $p_v = \gamma g \left[y \left(\frac{y}{C} + 1 \right) \right]^{-1}$ where $C = \frac{R h}{\mu' k}$

|| Walker's equation; $p_v = \frac{\gamma g R h}{B D'} \left[1 - \exp \left(\frac{-B D' y}{R h} \right) \right]$

Grain parameters in Walker's equations.

** Distribution factor was selected to be unity and not allowed to vary.

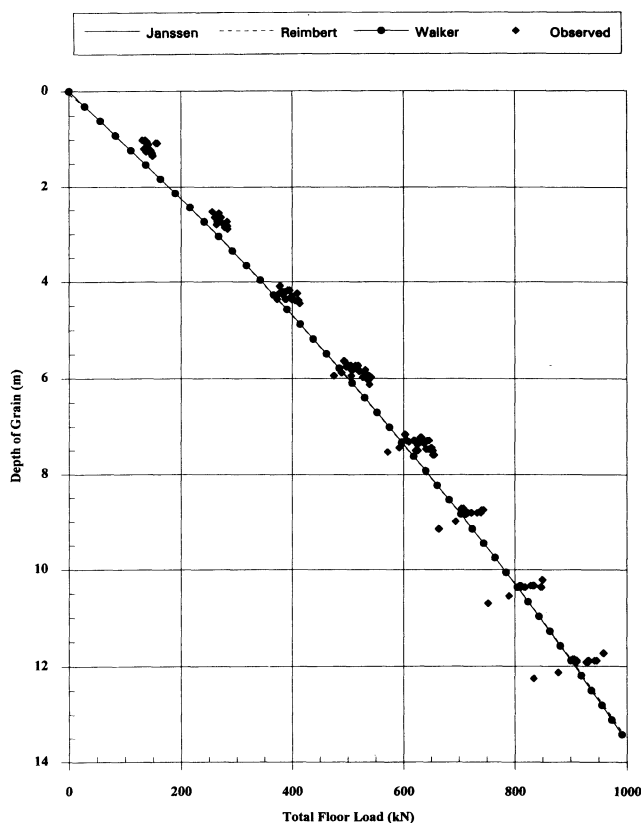


Figure 4—Nonlinear regression of three pressure prediction models to the observed total floor load during filling.

months. Many different variables including ambient temperature, solar radiation, and humidity influenced measured loads in addition to the maximum error of the load transducers and height measurement system.

The ratio of observed values of total floor load to the predicted values obtained from the different models is shown in figure 5. The observed values were nearly identical to the predicted values for depths of 4.6 m or more. Below a depth of 4.6 m the models were less accurate, because of the exponential shape of the data and the nonlinear regression technique utilized. The regression technique minimizes the difference between the data and the fitted curve, therefore the technique emphasizes agreement at the larger magnitudes which occur at the larger depths.

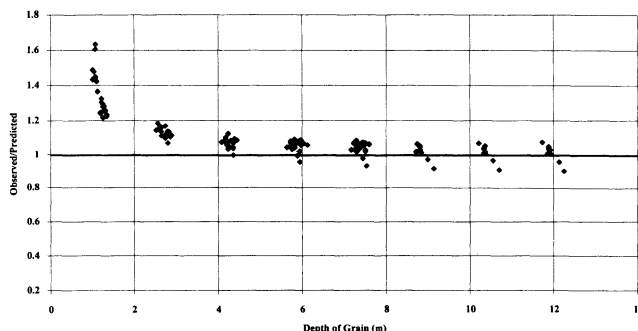


Figure 5—The ratio of the observed to predicted values of the total floor load values obtained from the three prediction models.

The fitted parameters of each existing model were considerably different than the commonly accepted design values. The value recommended by the ASAE Standard EP433 (1993) for the coefficient of friction of grain on galvanized steel was 3.4 to 9.7 times larger than the fitted values. Design values for the coefficient of friction are expected to vary from the actual measured values. The value of the coefficient of friction for wheat is a generalized value and does not consider material properties that influence friction. The test conducted on the grain used in this experiment for the apparent coefficient of friction of grain on galvanized steel blades was 1.4 to 4 times larger than the fitted values. The grain used for the coefficient of friction tests was a sample drawn from grain used in the full-scale test. The galvanized metal blade used was a random sample of galvanized steel and not an actual sample from the full-scale test bin. The material differences between the metal sample and the bin wall contributed to the differences between the coefficients of friction. Details of the apparent coefficient of friction experiment are reported in Schwab (1989). The values observed by Thompson (1980) were 1.6 to 4.6 times larger than the magnitudes of the apparent coefficient of friction that were measured. The low values of the coefficient of friction for wheat on galvanized steel are attributed to the smooth wall bin resulting from the extensive testing that was performed on the test bin prior to this study. Horabik et al. (1988) and Thompson (1980) reported a decrease in the dynamic wall load with each additional experiment. Thompson et al. (1987) showed that deposition of an oil or wax compound from wheat kernels on the steel surface reduces the coefficient of friction.

The total vertical wall load predicted by the three models using the parameters determined by the nonlinear regression of the total floor load was compared to the observed total vertical wall loads (fig. 6). These load values were estimated from the strain gage readings. The trend that exists in the data resembles the exponentially increasing values of vertical wall load at larger grain depths as predicted by the models.

A combination of factors contributed to the large variation in the strain gage measurements. The large variation observed in the total vertical wall loads was not a result of the uncertainties associated with the measuring error of the gages. The error for the total vertical wall loads was between 2 and 5% of the full-scale load of 300 kN for the different bin wall thicknesses. Larger variations in vertical wall loads were observed between the different measuring locations than between individual replications at a single measuring location. Additional variation occurred between the replications that spanned over four months.

The unexplained portion of the variability in the strain gage readings is the result of the overall measuring technique and the properties of the grain. The configuration of the bin wall panel with an exterior flange around the edges influenced the strain readings. Additional error would arise from the bending of the cylindrical shell (test bin). Wheat and other agricultural grains are also noted for the random stacking qualities which influence specific loading conditions (Horabik et al., 1988).

The comparison of the observed lateral pressures and those predicted by the models is shown in figure 7. The model predictions by Janssen and Walker are similar and

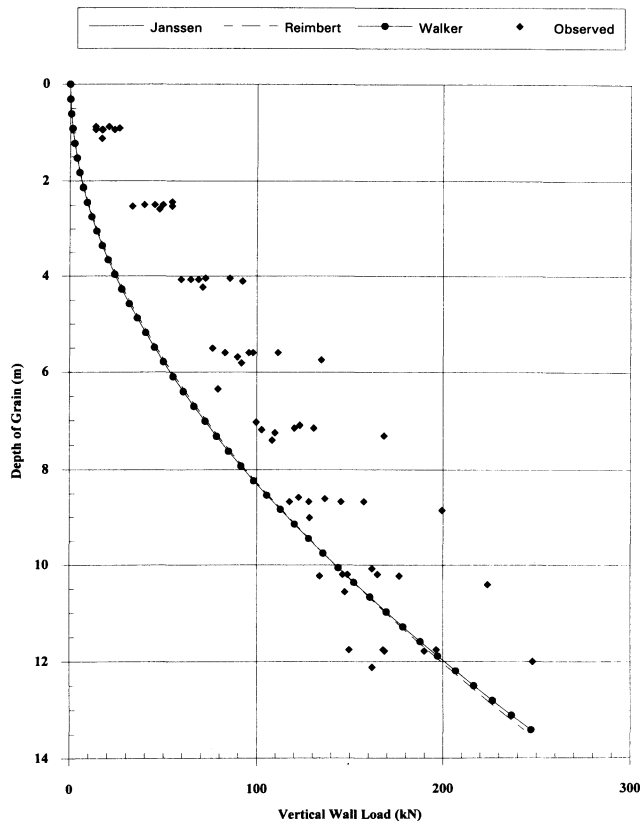


Figure 6—Comparison of the three pressure prediction models to the observed total vertical wall loads during filling.

are within the range of observed lateral pressures. Reimbert's model over estimates the observed lateral pressures. The same kind of variation observed in the vertical wall loads is present in the lateral pressures because the method of calculation uses the same strain gage measurements that was used in the vertical wall loads. The error for the lateral pressures ranged from 1 to 4% of the full-scale load of 40 kPa for different bin wall thicknesses.

The total weight of the grain on the bin floor was subtracted from the total weight of grain in the bin to estimate the total vertical wall load. The comparison of the estimated total vertical wall load calculated from the total floor loads and predictions by the models using the parameters from the floor load regression is shown in figure 8. The total vertical wall loads calculated from the total floor loads and the prediction models coincide. The magnitude of the total vertical wall loads calculated from the total floor loads was less than the observed values obtained with the strain gages. The values calculated from the total floor loads represent an average total vertical wall load that removed the localized loading and reduced the variation of the total vertical wall load.

The average distribution of the total grain weight was determined to be approximately 83% on the bin floor and 17% on the bin wall for an H/D ratio of 3. This distribution differs from the observed distributions of floor and wall loads found by Jamieson (1903). Jamieson observed that 85% of the total grain weight was on the bin wall for a H/D ratio of 5. Thompson et al. (1982) observed that 20% of the

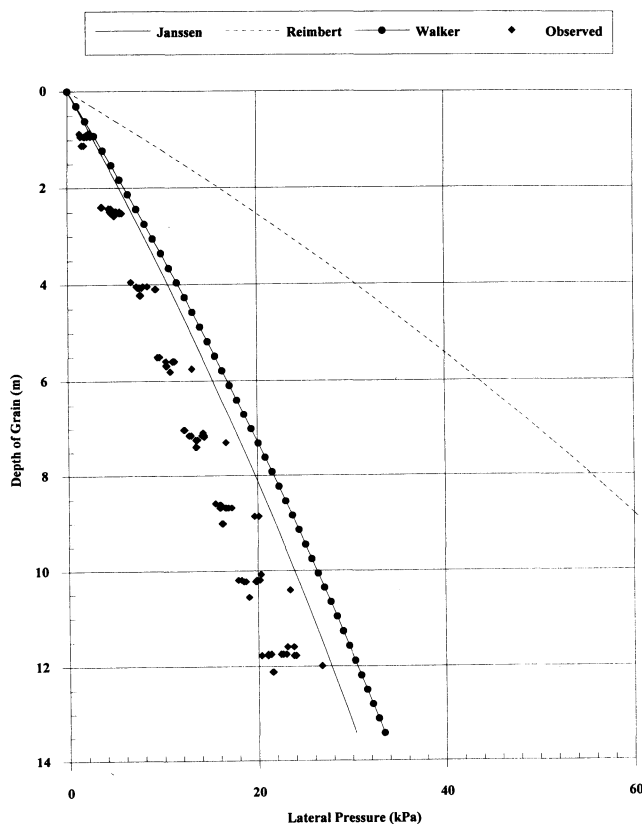


Figure 7—Comparison of the three pressure prediction models to the observed lateral pressure during filling.

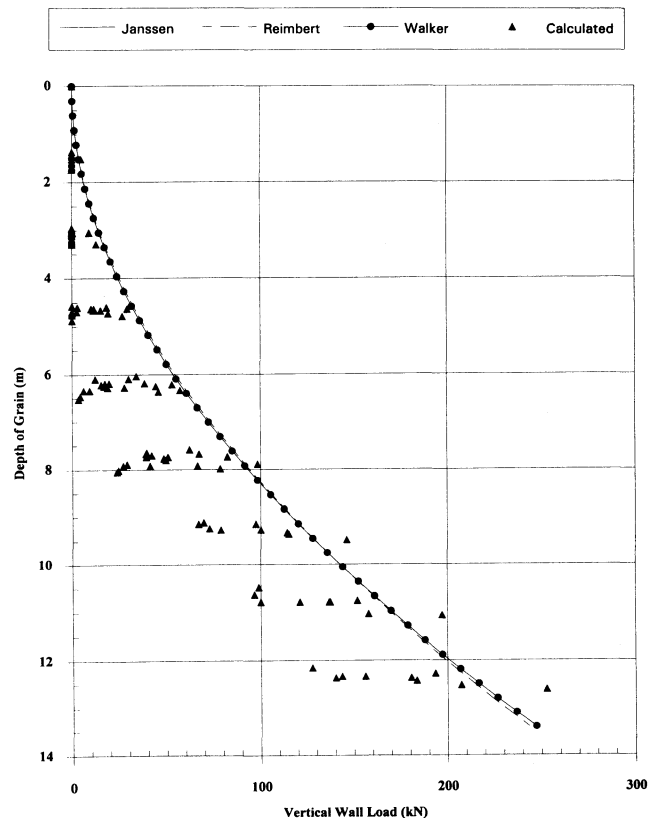


Figure 8—Comparison of the three pressure prediction models to the total vertical wall loads calculated from the total floor loads during filling.

total grain weight was on the bin wall for an H/D ratio of 4. The differences between the results of Jamieson (1903), Thompson et al. (1982), and this experiment are the different H/D ratios used by the different studies and the scaling factor between the full-scale and model tests. As the H/D ratio increases, the percentage of the load carried by the wall increases.

RADIAL VARIATION

Radial location significantly influenced the vertical pressure at the 0.01 significance level at both H/D ratios as determined with the ANOVA test (SAS, 1982). The magnitude of the vertical pressure as a function of bin radius and grain depth is illustrated in figure 9. Duncan's test was used at the 0.05 significance level to determine if the mean vertical pressures for radial locations were significantly different for a discrete grain depth. Mean vertical pressures for radial locations 0.32, 0.56, 0.72, and 0.84 were not significantly different, but the mean vertical pressure for radial location of 0.95 was significantly different than the mean vertical pressure for the other radial locations. No statistical difference of the vertical pressure distribution was determined between common grain depths of the 1.8 and 3 H/D ratio tests for radial locations of 0.32, 0.84, and 0.95. Radial locations of 0.56 and 0.72 were determined to have significantly different magnitudes of vertical pressure for different H/D ratios at the 0.01 significance level.

The vertical pressure patterns observed by Bovey (1904), Dale and Robinson (1954), Saul (1953), and others exhibited similar characteristics to the measured vertical pressures shown in figure 9. The lower vertical pressure near the wall and a larger vertical pressure near the center are two common characteristics of vertical pressure patterns. The vertical pressure pattern found by Suzuki et al. (1985) has the third characteristic observed in

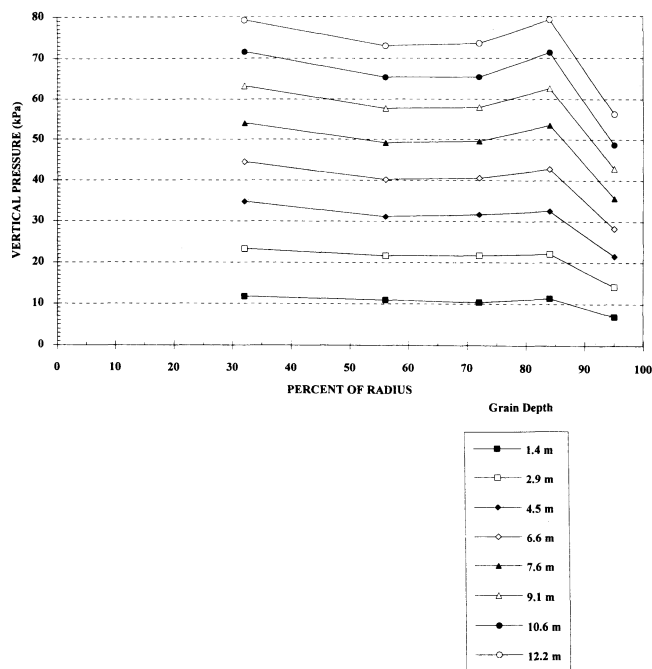


Figure 9—Radial variation of vertical pressure at different grain depths during the filling stage for H/D ratio of 3.

the measured vertical pressure during filling that other researchers did not measure. The maximum of vertical pressure in the center was common to most reported results, but the second peak between the center and wall that was observed in these tests has been reported only by Suzuki.

SUMMARY AND CONCLUSIONS

Radial variation of vertical pressure was observed during the filling procedure for a full-scale bin. The measured floor loads were determined to be influenced at the 0.01 significance level by the radial locations for both H/D ratios of 1.8 and 3.0. As the depth of grain increased, the shape of the radial variation in the vertical pressure changed. The distribution of the vertical pressure at low H/D ratios appeared to have a flat line uniform distribution, but as the grain depth increased the non-uniformity of the vertical pressure distribution across the bin radius became more pronounced.

This investigation provides measured values of loads and pressures that were collected using a full-scale bin and wheat. This allows comparison of predictions of mathematical models to experimental results without the use of scaling factors. The conclusions based on the results recorded during the full-scale tests are:

- Vertical pressure distribution is dependent on radial location and is not uniformly distributed.
- The distribution of grain weight for the test bin with an H/D ratio of 3 is 83% on the floor and 17% on the walls.
- The shape of the prediction equation follows the measured values of total floor load, lateral pressure, and vertical wall load.
- The regressed parameters for the prediction equations are considerably different than the standard design values.

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